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A Measurement of the D_s^+ Lifetime

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A high statistics measurement of the D_s^+ lifetime from the Fermilab fixed-target FOCUS photoproduction experiment is presented. We describe the analysis of the two decay modes, $D_s^+ \to \phi(1020)\pi^+$ and $D_s^+ \to \overline{K}^*(892)^0 K^+$, used for the measurement. The measured lifetime is 507.4±5.5 (stat.)±5.1 (syst.) fs using 8961±105 $D_s^+ \to \phi(1020)\pi^+$ and 4680±90 $D_s^+ \to \overline{K}^*(892)^0 K^+$ decays. This is a significant improvement over the present world average.

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Experimental measurements of charm lifetimes have given guidance towards a theoretical description of strong interactions at low energy scales [1, 2]. For example, the ratio of the D_s^+ and D^0 lifetimes gives information on the *weak annihilation* contribution to the total decay [3–6]. Not only is this important for improving our theoretical understanding of strong interactions, but the theoretical tools used to calculate lifetimes are the same or similar to those used in other areas, for example to extract $|V_{cs}|/|V_{cd}|$ and $|V_{cb}|$ in charm and bottom decays, or to calculate the b-particle lifetimes [7, 8].

The data used were collected by the FOCUS collaboration in the 1996–1997 fixed-target run at Fermi National Accelerator Laboratory. The FOCUS spectrometer is an upgrade of the spectrometer used in the E687 photoproduction experiment [9]. In the majority of the data used for this measurement (Run Period B) the vertex region consists of four BeO targets and 16 planes of silicon strip detectors (SSD). Two of the SSD planes were placed immediately downstream of the second target, and two immediately downstream of the fourth (most downstream) target. About 20% of the D_s^+ decays used in this anal-

ysis were from data taken earlier in the data-taking run (Run Period A) without the four SSD planes in the target region [10]. Momentum analysis was done using five multiwire proportional chambers and two magnets with opposite polarities. Three multicell threshold Čerenkov counters were used for particle identification [11].

The $D_s^+ \to \phi(1020)\pi^+$, $\phi(1020) \to K^-K^+$ and $D_s^+ \to \overline{K}^*(892)^0K^+$, $\overline{K}^*(892)^0 \to K^-\pi^+$ resonant decay modes [22] are used because they have much better signal-to-background than inclusive $D_s^+ \to K^-K^+\pi^+$ decays.

All $K^-K^+\pi^+$ candidates are tested to see if they form a vertex with a confidence level greater than 1%. The candidate D_s^+ momentum vector is then projected to search for a production vertex with one or more tracks. As many tracks as possible are included in the production vertex so long as the vertex confidence level is larger than 1%. The production vertex is required to be within one of the four targets. To largely eliminate non-charm backgrounds, the separation L between the production and decay vertices is required to be larger than $6\sigma_L$ where σ_L is the calculated error on L.

The $\phi(1020)\pi^+$ ($\overline{K}^*(892)^0K^+$) decay mode candidates are required to have K^+K^- ($K^-\pi^+$) masses within two sigma of the fitted $\phi(1020)$ ($\overline{K}^*(892)^0$) mass. Also the magnitude of $\cos\theta^*$ must be larger than 0.3 (0.6) for the $\phi(1020)\pi^+$ ($\overline{K}^*(892)^0K^+$) decay mode candidates, where θ^* is the angle between the K^- and the π^+ (K^+) in the $\phi(1020)$ ($\overline{K}^*(892)^0$) center-of-mass frame. For the $\overline{K}^*(892)^0K^+$ decay mode, the K^+K^- invariant mass must not be within two sigma of the $\phi(1020)$ mass to ensure statistically independent samples in the two decay modes. Each track in the $K^-K^+\pi^+$ candidate combination must also satisfy a minimal Čerenkov particle identification criteria. To further reduce the $D^+ \to K^-\pi^+\pi^+$ contamination by an additional factor of 15 in the $D_s^+ \to \overline{K}^*(892)^0K^+$ candidate sample, the kaon with the same sign as the pion is required to have a kaon probability that is larger than its pion probability by a factor of e^3 [11].

The $K^-K^+\pi^+$ invariant mass plots for data are shown in Fig. 1. The fits shown are to a Gaussian signal and a quadratic background function which yields 8961 ± 105 $\phi(1020)\pi$ and 4860 ± 90 $\overline{K}^*(892)^0K$ reconstructed D_s^+ decays. The lifetime analysis uses $K^-K^+\pi^+$ candidates in a signal region that is within $\pm 2\sigma_m$ of the fitted D_s^+ mass (SR), where σ_m is the fitted Gaussian width of the D_s^+ peak. Candidates within two symmetric sideband regions (SBR), each of width $2\sigma_m$ and centered at $\pm 5\sigma_m$ from the fitted D_s^+ mass, are used to represent the lifetime distribution of background in the SR. The SR and SBR are shown in Fig. 1.

For the lifetime analysis we use the reduced proper time, $t' = (L - 6\sigma_L)/\beta\gamma c$. The use of the reduced proper time ensures that only a small acceptance correction to the lifetime distribution is needed [12]. The average proper time resolution for this decay sample (51 fs for Run Period A and 43 fs for Run Period B) is small enough compared to the lifetime to use a binned likelihood method. We fit the $\phi(1020)\pi$ and $\overline{K}^*(892)^0K$ decay modes separately. For each decay mode the Run Period A and B data are used in a combined fit.

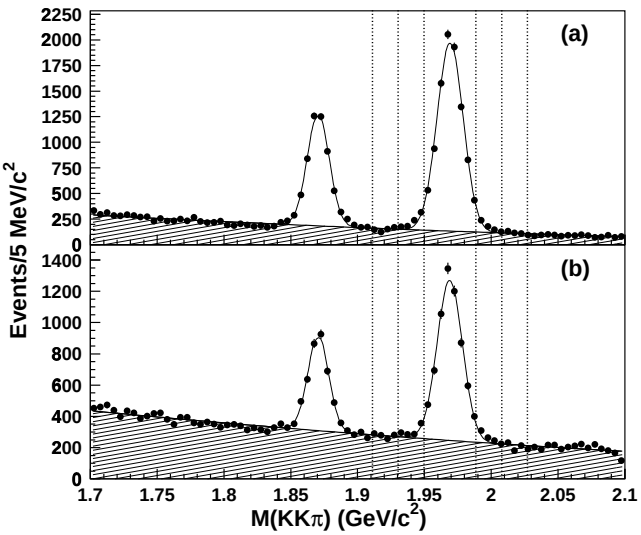

FIG. 1: The $K^+K^-\pi^+$ invariant mass distributions for the (a) $\phi(1020)\pi^+$ and (b) $\overline{K}^*(892)^0K^+$ decay modes. The data is given by the points while the line gives the fit with the hatched region showing the fitted background level. The vertical dotted lines gives the D_s^+ signal and sideband regions.

For each of the run periods A and B, the t' distributions for the decays in the SR and SBR are binned into two separate histograms from 0–3 ps in 60 fs bins. The observed number of decays in the $i^{\rm th}$ t' bin is s_i^A for the SR and b_i^A for the SBR, where A refers to Run Period A. The t' distribution of the SBR is used as a measure of the lifetime distribution of background events in the SR. Thus the expected number of decays ($n_i(A)$) in the $i^{\rm th}$ t' bin of the SR for Run Period A is given by:

$$n_i(A) = S_A \frac{f_A(t_i')e^{-t_i'/\tau}}{\sum_i f_A(t_i')e^{-t_i'/\tau}} + B_A \frac{b_i^A}{\sum_i b_i^A}\,, \qquad (1)$$

and the likelihood for Run Period A is given by

$$\mathcal{L}_A = \prod_i \frac{n_i(A)^{s_i^A} e^{-n_i(A)}}{s_i^A!} \times \frac{(\alpha_A B_A)^{N_b^A} e^{-\alpha_A B_A}}{N_b^A!}\,. \qquad (2)$$

S_A is the total number of signal events, B_A is the total number of background events in the SR, and $S_A + B_A = \Sigma s_i^A$. The total number of events in the SBR is $N_b^A = \Sigma_i b_i^A$ and α_A is the ratio of the number of events in the SBR to the number of background events in the SR. The value of α_A is obtained from the fit to the invariant mass distribution and is very close to 1. There is a similar likelihood for Run Period B and the likelihood that is maximized is $\mathcal{L} = \mathcal{L}_\mathcal{A} \times \mathcal{L}_\mathcal{B}$. The fit parameters are B_A, B_B, and τ.

The effects of geometrical acceptance, detector, trigger and reconstruction efficiencies, and absorption are

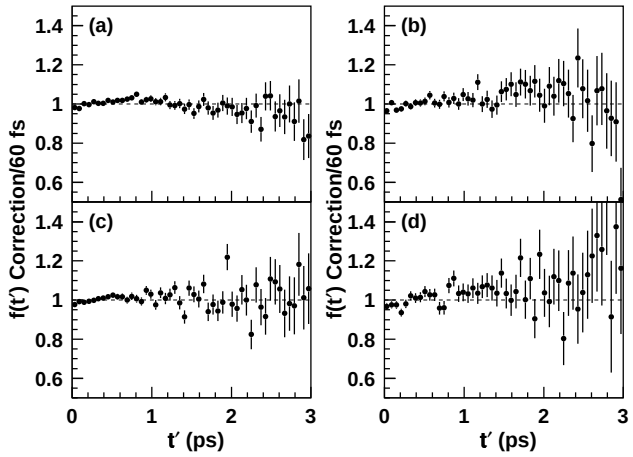

FIG. 2: The $f(t')$ correction functions for the two decay modes and two run periods (a) $\phi(1020)\pi$ Run Period B; (b) $\phi(1020)\pi$ Run Period A; (c) $\overline{K}^*(892)^0K$ Run Period B; and (d) $\overline{K}^*(892)^0K$ Run Period A. Deviation from a flat line indicates the correction from a pure exponential.

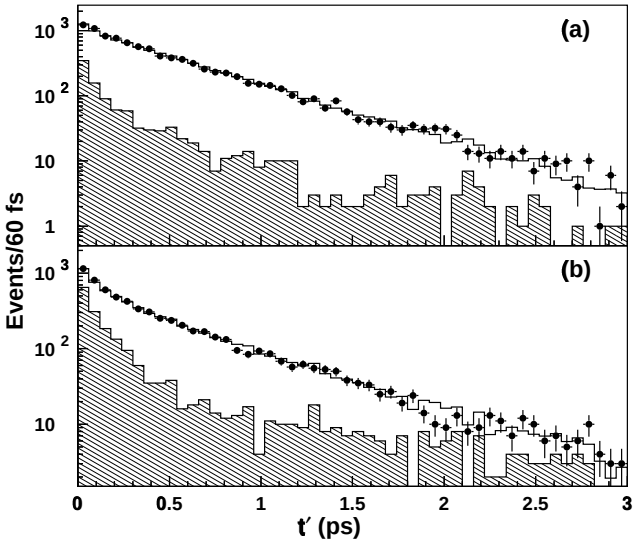

FIG. 3: The lifetime distribution for all decays in the data SR (points), and the fit (histogram). The shaded distribution shows the lifetime distribution of the background component in the SR. The data and fit are shown for Run Periods A and B combined in the same plot for the two decay modes (a) $\phi(1020)\pi$ and (b) $\overline{K}^*(892)^0K$.

given by the $f(t')$ correction function. The $f(t')$ function is determined using a detailed Monte Carlo (MC) simulation of the experiment where the production (using PYTHIA [13]) was tuned so that the production distributions for data and MC matched. A full coherent $D_s^+ \to K^-K^+\pi^+$ decay was simulated using results from FOCUS [14]. The $f(t')$ distributions are shown in Fig. 2.

We obtain fitted lifetimes of 507.60 ± 6.46 fs and 506.90 ± 10.60 fs for the $\phi(1020)\pi$ and $\overline{K}^*(892)^0K$ decay modes, respectively. The fit confidence levels are 2.0% and 0.13%, respectively. A discussion of these small fit confidence levels is given below. The lifetime distribution of all decays in the SR are shown in Fig. 3 together with the fit and the level of background contained in the SR.

Detailed studies were performed to determine the systematic uncertainty in the lifetime measurement.

The $f(t')$ correction reduces the fitted lifetime by 0.80%. We studied the uncertainty in this correction. We verified that the MC reproduces the data D_s^+ longitudinal and transverse momenta, the multiplicity of the production vertex, $\cos\theta^*$, and the decay length and proper time resolutions. A sensitive check of the acceptance and efficiency part of the MC correction was done using high statistics $K_S^0 \to \pi^+\pi^-$ decays. Short-lived K_S^0 decays were reconstructed using the same analysis methods in the same decay region as the D_s^+ decays. Since the K_S^0 lifetime is well known, we can determine the $f(t')$ correction in data and compare it to that obtained in our MC simulation. The agreement is excellent but was limited in sensitivity by both data and MC statistics. Using this sensitivity as the level of the uncertainty in the $f(t')$ correction, we determine a systematic uncertainty due to this correction of $\pm 0.69\%$. Possible time dependent systematic effects were looked for by splitting the data into different time periods and comparing the fitted lifetimes. We also compared the separate fitted lifetimes for decays originating from each of the four targets. No systematic uncertainties were found in these comparisons.

Our limited knowledge of the production and decay of the D_s^+ could contribute to a systematic uncertainty. This was studied using different MC simulations where the production parameters and the resonance substructure of the decay were varied over reasonable ranges. Production systematics were also studied by splitting the data into different bins of total and transverse D_s^+ momenta, primary vertex multiplicity, and by comparing the fitted lifetimes for particles and anti-particles. We found no evidence of systematic effects, however, variations of the fitted lifetimes in these studies led us to assign a systematic uncertainty of $\pm 0.23\%$ due to our limited knowledge of D_s^+ production and decay.

The systematic uncertainty due to absorption of the D_s^+ and daughter particles was determined by varying the D_s^+ interaction cross-section [23] by 100% and the daughter particle interaction cross-sections by 50% in the MC. It was also studied by comparing the lifetimes of decays occurring inside and outside of the target, and by comparing the lifetimes for decays where the D_s^+ was produced in the upstream half of each target with those produced in the downstream half of the same target. We determined a systematic uncertainty of $\pm 0.38\%$ due to absorption.

In order to use the reduced proper time we must be able to correctly model our proper time resolution. This was verified by comparing the distributions for data and MC and by studying splits of the data sample that can be

sensitive to resolution effects. This included splits in t' resolution and reconstructed invariant mass and varying the t' bin width and changing the fitted range for t'.

The lifetime distribution of the background in the SR is assumed to be well represented by the SBR. The uncertainties that arise because of this assumption were determined by a number of studies.

The contamination from $D^+ \to K^-\pi^+\pi^+$, and $\Lambda_c^+ \to K^-p\pi^+$ decays misidentified as $K^-K^+\pi^+$ decays were determined in our sample. As a fraction of the total $D_s^+ \to \phi(1020)\pi$ ($D_s^+ \to \overline{K}^*(892)^0K$) signal in the SR, we found the above two backgrounds contribute 0.7% (3.0%) and 0.2% (2.5%), respectively. The small contribution of these reflection backgrounds mean they give rise to insignificant uncertainties. This was verified in a test by using stronger particle identification and by explicitly eliminating them by cutting out the appropriate mass regions.

The background lifetime uncertainty was further investigated by using symmetric sidebands of different widths (2–4σ_m), and located at different separations from the signal region (± 4 to $\pm 6\sigma_m$). Variations in particle identification and vertexing selection were used to study the lifetime with changes in the signal/background ratio and this showed no significant effect.

Finally, an independent analysis which did not rely on knowledge of the background lifetime distribution was performed. In this analysis the data were split into fifteen 150 fs wide reduced proper time bins from 0–2.25 ps and one 750 fs wide bin from 2.25–3 ps. The numbers of $D_s^+ \to \phi(1020)\pi^+$ and $\overline{K}^*(892)^0K^+$ decays in each bin were determined in a mass fit and the yields for the two decay modes separately fitted to an exponential decay distribution modified by a $f(t')$ correction function. No significant systematic effects were found. To account for the variations of the lifetime in the various background studies we assign a background systematic uncertainty of $\pm 0.16\%$ ($\pm 1.09\%$) for the $\phi(1020)\pi$ ($\overline{K}^*(892)^0K$) decay mode.

A mini-Monte Carlo test of the fit method was done to check the accuracy of the fit errors and to look for possible biases in the fit. We generated 1000 independent data samples from the best fit to the data. Each of these data samples were fit as real data. Distributions of fitted values showed a small bias in the fitted lifetime which is accounted for in a Fit Method systematic uncertainty (see Table I). This study also showed that the fit error underestimates the true statistical uncertainty in the $\phi(1020)\pi$ ($\overline{K}^*(892)^0K$) mode by 4.8% (14.7%). The statistical errors on the lifetimes quoted in this paper have been corrected for this effect. These fit properties are due to the background at higher lifetimes and because the $b_i^{A,B}$ in Eq. (1) are fixed in the fit. The latter also leads to the small reported fit confidence levels. When bin-to-bin fluctuations in the observed $b_i^{A,B}$ are accounted for in the calculation of the χ^2, the fit confidence levels for $\phi(1020)\pi$ and $\overline{K}^*(892)^0K$ become 8.8% and 16%, respectively. The goodness of fit is further verified by using background lifetime distributions taken from fits to the data sideband distributions instead of the actual ($b_i^{A,B}$) entries. This fit method gives consistent lifetimes and fit confidence levels of 9.2% and 18% for $\phi(1020)\pi$ and $\overline{K}^*(892)^0K$, respectively.

TABLE I: Contributions to the systematic uncertainty.

Contribution	Systematic Uncertainty (%)		
	$\phi(1020)\pi$	$\overline{K}^*(892)^0K$	Combined
Acceptance	± 0.69	± 0.69	± 0.69
Production	± 0.23	± 0.23	± 0.23
Absorption	± 0.38	± 0.38	± 0.38
Backgrounds	± 0.16	± 1.09	± 0.41
Fit Method	± 0.12	± 1.07	± 0.38
Time Scale [15]	± 0.12	± 0.12	± 0.12
Total	± 0.85	± 1.74	± 1.00

TABLE II: Comparison of D_s^+ lifetime measurements and $\tau(D_s^+)/\tau(D^0)$ ratios. The PDG value of the D^0 lifetime [16] is used in the ratios, except for the FOCUS ratio for which the FOCUS measurement is used [17].

Experiment	$\tau(D_s^+)$ fs	$\tau(D_s^+)/\tau(D^0)$
E687 [18]	$475 \pm 20 \pm 7$	1.158 ± 0.052
E791 [19]	$518 \pm 14 \pm 7$	1.262 ± 0.038
CLEO II.5 [20]	$486.3 \pm 15.0^{+4.9}_{-5.1}$	1.185 ± 0.039
SELEX [21]	$472.5 \pm 17.2 \pm 6.6$	1.152 ± 0.045
FOCUS (this result)	$507.4 \pm 5.5 \pm 5.1$	1.239 ± 0.017

We have measured the D_s^+ lifetime to be 507.4 ± 5.5 (stat.) $\pm$ 5.1 (syst.) fs using 8961 ± 105 $D_s^+ \to \phi(1020)\pi^+$ and 4680 ± 90 $D_s^+ \to \overline{K}^*(892)^0K^+$ decays from the Fermilab FOCUS photoproduction experiment. We also determined the ratio of our D_s^+ lifetime to our D^0 lifetime [17] to be 1.239 ± 0.014 (stat.) ± 0.009 (syst.), where the systematic uncertainty in the ratio is reduced by eliminating common systematic contributions. Table II compares our measurement with recent published results. This measurement represents a significant improvement in precision.

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[22] The charge conjugate mode is implicitly implied unless otherwise stated.
[23] The D_s^+ cross section is taken to be half the neutron cross section.